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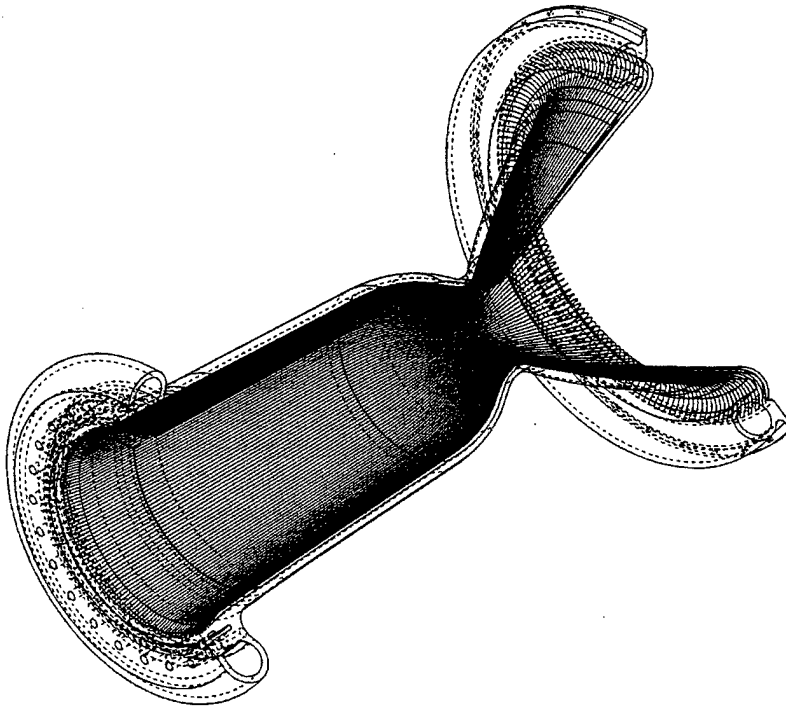
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(Statement A)

AIAA 99-2599

DEVELOPMENT AND TEST OF AN
ADVANCED EXPANDER COMBUSTOR

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ABSTRACT

This paper discusses development and test of an advanced expander combustion chamber for a 50,000 pound (222.4 kN) thrust Upper Stage Expander Cycle Engine. The chamber is being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Propulsion Technology (IHRPT) program. The Advanced Expander Combustor is designed to provide increased heat pick-up to the coolant and improved system thrust to weight, increased specific impulse, and increased reliability. These benefits will be accomplished and demonstrated through design, development, and test of this high heat flux, compact thrust chamber capable of supporting a chamber pressure of 1375 psia (97 kg/cm²) in an expander cycle configuration.

INTRODUCTION

Remove
The Air Force, Army, Navy, and NASA have implemented a three phase, 15-year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHRPT), establishes performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level demonstrator to validate performance to the IHRPT system level goals. Pratt & Whitney Liquid Space Propulsion, under contract to the United States Air Force Research Laboratory (contract F04611-95-C-0123), is developing the Advanced Expander Combustor (AEC) combustion chamber. This combustion chamber is designed to be used with the Advanced Liquid Hydrogen (ALH) turbopump (Ref. AIAA 99-2190 *Design and Test Results of an Advanced Liquid Hydrogen Turbopump*) in the 50k LOX/Hydrogen Upper Stage Demonstrator (Ref. AIAA 99-2599 *Development Status of a 50k LOX/Hydrogen Upper Stage Demonstrator*). This demonstrator will be test fired in late 2000 to demonstrate the IHRPT LOX/LH₂ boost/orbit transfer propulsion area Phase I goals. These system level goals include; a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware/support costs, and a 25% improvement in reliability relative to the current state-of-the-art engine, baseline the P&W RL10A-3-3A.

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Pratt & Whitney, in cooperation with the United States Air Force Research Laboratory, has developed an advanced upper stage expander engine model. The purpose of this model is to establish the individual component requirements necessary to ensure the IHRPT Phase I system level goals. The cycle model was used to establish the performance, cost, weight, and thermodynamic operating requirements of the AEC. The component goals, established for the AEC to support the resulting cycle and IHRPT goals, are as follows:

Increase coolant heat pick-up by 300% with respect to the current state-of-the-art RL10A-3-3A baseline.

Maintain coolant pressure drop to within 50 psia (3.5 kg/cm²) with respect to the current state-of-the-art RL10A-3-3A baseline.

Flight weight target of 65 pounds (29 kg) for the combustion chamber.

Maintain combustion chamber fabrication costs of the current state-of-the-art RL10A-3-3A baseline.

The AEC design accomplishes these goals. The heat pick-up is increased 300% while simultaneously reducing the required heat exchanger area to approximately 37% of the RL10A-3-3A baseline. Similarly, the heat transfer to normalized pressure drop is increased by a factor of 2.1. Achievement of the above AEC component goals results in a 10% improvement in engine thrust-to-weight and 1% improvement in specific impulse relative to the baseline RL10A-3-3A.

DISCUSSION

The simplicity of the expander-cycle engine offers the ability of placing payloads into orbit at lower cost. Improving performance of the system through increases in chamber pressure while maintaining the same dimensional envelope is highly desired. Current expander cycle engines are limited in their ability to increase chamber pressure, due to the low heat transfer afforded by the materials used in the combustion chamber. Development of an advanced-technology combustion chamber that increases chamber pressure and provides more performance while maintaining reliability and operability is the key to advancing the ability of the expander engine.

An expander-cycle rocket engine cools the chamber/nozzle components with the engine fuel flow while powering the turbopumps with the energy picked up by the cooling process. The relatively benign turbine inlet temperature created by this cycle results in

weight, cost, and reliability advantages over other cycles (i.e., gas generator, staged combustion). The elimination of combustion devices that drive turbopumps further enhances these advantages. Expander-cycle engines have lower turbopump pressure requirements than staged combustion engines and higher performance potential than gas generator cycles. To reach the true potential of the expander-cycle engine (i.e., highest thrust in the smallest dimensional envelope) the combustion chamber heat pickup must be maximized in order to maximize power to the drive turbines. Development of the advanced expander-cycle engine depends on this technology issue being resolved through the design, fabrication, and testing of an advanced thrust chamber.

P&W created an advanced expander engine model, which meets the IHRPT Phase I system level goals, from which component goals could be determined. The P&W RL10A-3-3A is the baseline for the IHRPT goals and was used as the starting point for developing the advanced expander engine cycle. The RL10A-3-3A has 16,500 pound (7484 kg) vacuum thrust, Specific Impulse of 442.5 seconds, and a thrust-to-weight ratio of 53. It utilizes a two-stage turbine driven by the expanded hydrogen from the combustor and nozzle cooling tubes. The RL10 turbine drives

both the two-stage hydrogen turbopump and, through a gearbox, the single stage Liquid Oxygen (LOX) turbopump. The maximum cycle pressure is approximately 1100 psia (77.33 kg/cm²) with a chamber pressure of 470 psia (33 kg/cm²). The expander cycle developed for the RL10, shown in Figure 1, is used in each member of the RL10 family, covering the 16,500 to 24,750 pound (7484 - 11226 kg) thrust range. The advanced expander engine cycle, based on the RL10 cycle, was established to support the IHRPT Phase 1 goals. It will allow further growth to 50,000 - 80,000 pounds (22,679 - 36,287 kg) while maintaining the benefits of the RL10 family history.

The growth potential of the current RL10 family is limited by the fuel pump discharge pressure which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. While the tubular configuration provides better heat pickup than current milled channel combustor, the moderate conductivity of the RL10 steel tubes limits their heat load capacity per unit area and heat pick up. The ability to transfer more heat across the chamber cooling wall is essential to providing the increased energy required for higher turbopump output, chamber pressure, and thrust, in the advanced expander cycle.

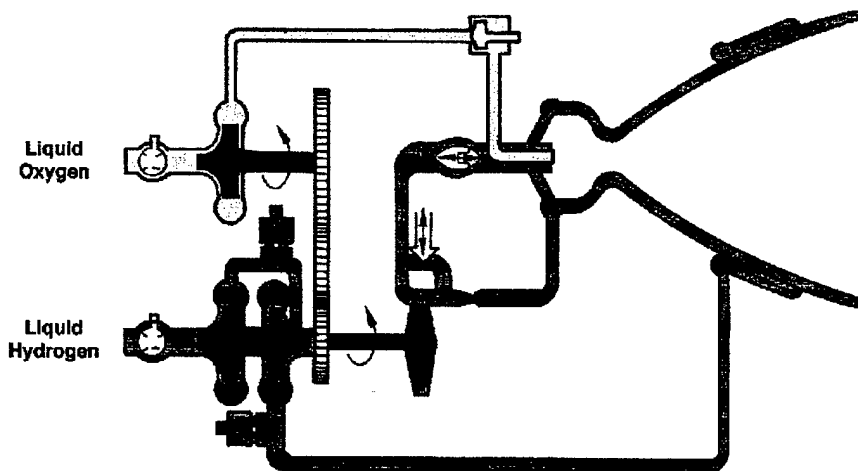


Figure 1 - RL10 Expander Cycle System with Gearbox

Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice of material properties such as strength, Low Cycle Fatigue (LCF) characteristics, and oxidation/erosion capability. This problem has been solved by the development of PWA 1177 dispersion strengthened copper which provides improved material

strength, LCF capability, and conductivity. The Advanced Expander Combustor (AEC) being developed for the AFRL on contract F04611-95-C-0123 uses PWA 1177 to provide the increased heat transfer and resultant energy required to support the advanced expander engine cycle.

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The additional heat load capacity provides the required turbine input energy needed to support an increase in the turbopump discharge pressures, allowing an increase in chamber pressure. Analysis of an expander cycle with the improved heat load capacity supports a stable expander cycle operating at a chamber pressure of 1375 psia (96.7 kg/cm²) with a maximum cycle pressure of 4600 psia (323.4 kg/cm²) at the ALH fuel turbopump discharge. The final system balance provides a heat load capacity of 22,833 Btu/sec (24M

N-M/sec) available to drive both the ALH fuel turbopump and the LOX turbopump with at least 5% margin remaining for roll control thrusters, boost pump drive, or equivalent bypass requirements.

The advanced expander engine cycle, configured to meet IHPRPT Phase I goals, is shown in Figure 2. The predicted advanced expander engine system performance is summarized in Table 1.

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WHAT'S NEW

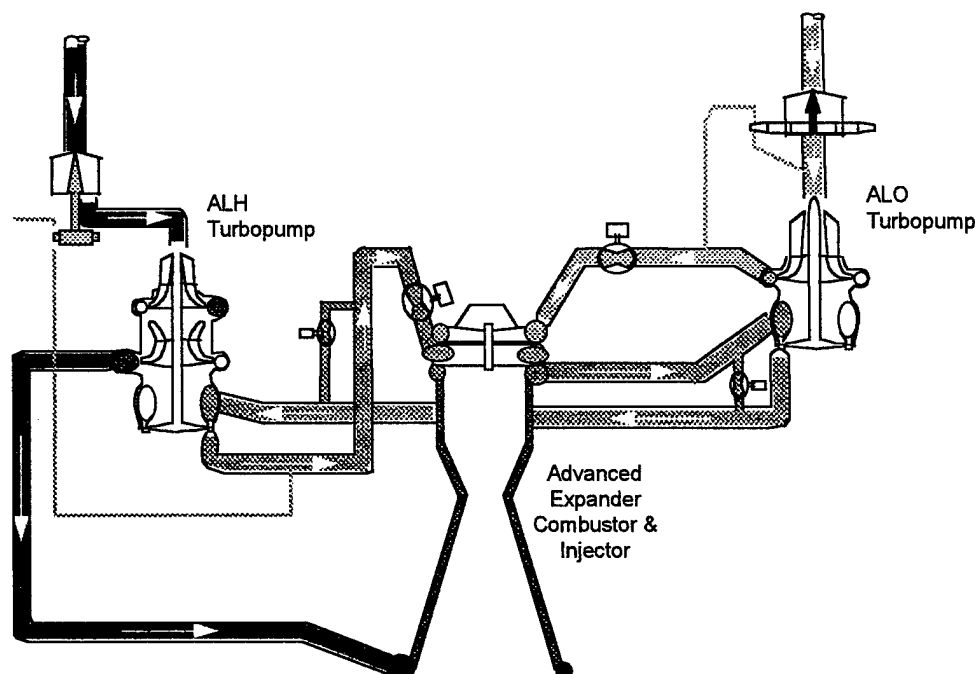


Figure 2. Advanced Expander Engine Cycle Schematic

Table 1. Advanced Expander Engine Cycle Summary

Vacuum Thrust, lbf	50,334	Chamber Pressure, psia	1375
Engine Mixture Ratio	6.00	Combustion C* Efficiency	0.99
Chamber Mixture Ratio	6.11	Chamber Coolant Q, Btu/s	22,833
Engine Flowrate, lbm/sec	112.0	Chamber Length, in	26.0
Del. Vacuum Isp, sec	447.0	Chamber Contraction Ratio	4.65
Throat Area, in**2	19.09	C*, Char. Velocity, ft/s	7553
Nozzle Efficiency, Cs	0.995	Nozzle AR	61
Weight Estimate, lb	708	Nozzle Exit Diameter, in	39.6
Thrust to Weight	71	Turbine Bypass, %	5.4

THE ADVANCED EXPANDER COMBUSTOR DESIGN

The AEC design goals are to maximize coolant heat pick-up with a minimum coolant pressure drop and minimum chamber weight and production cost. The accommodation of high heat flux levels requires thermally compliant chamber materials and geometries with high strength liners. The enabling design feature of the AEC is the use of a high strength high conductivity copper alloy, Pratt & Whitney PWA 1177, in a tubular combustor configuration. The AEC has been designed to provide:

- A naturally compliant pressure vessel shape for reduced strain levels in response to thermal stresses,

- Reduced pressure losses of the hydrogen coolant, and
- Increased surface due to tube crowns allows maximum heat pick-up,

The AEC design requirements were distributed to a design team including mechanical, thermal, structural, and fabrication specialists. Establishment of the physical design as well as integration of the individual sub-elements among the various specialists was the responsibility of the mechanical design specialist assigned to lead the team. The AEC is shown in cross section in Figure 4.

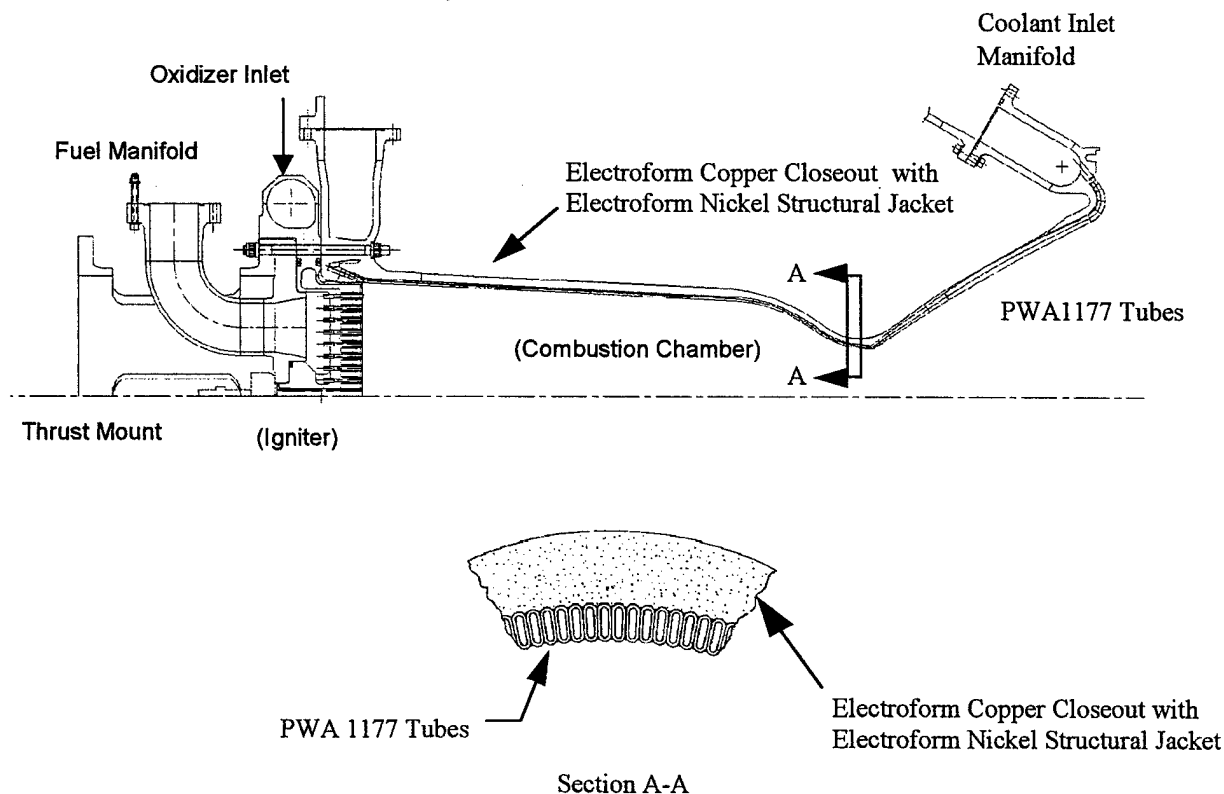


Figure 4. Cross section of the Advanced Expander Combustor

Copper Tubular Liner Design

The challenges of the AEC liner design were to maximize coolant heat pick-up, minimize coolant pressure drop and increase strain range tolerance and

ductility, maintain liner material properties throughout the fabrication process, and increase the liner creep strength.

Following a thorough examination of various options in chamber construction, P&W selected a copper-based

tubular thrust chamber. The most significant feature is the use of a new copper alloy (PWA 1176) coupled with an improved processing technique (PWA 1177). Using P&W's Rapid Solidification Rate (RSR) powder metallurgy technology, a new, optimized alloy was created that enables the fabrication of high-strength, temperature-resistant copper tubes. In final form, these PWA 1177 tubes can withstand repeated exposure to fabrication temperatures in excess of 1800°F and still retain yield strength five times greater than copper alloys used in current rocket thrust chambers. PWA 1176/1177 is essentially pure copper with a dispersion of fine aluminum oxide particles (alumina, Al_2O_3). The alumina dispersoids allow work hardened strength to be retained, especially at elevated temperatures, without significant loss of thermal conductivity. The result is an advanced high-strength copper alloy that maintains its strength during high temperature manufacturing processes.

In addition to the use of this superior copper alloy, the tubular configuration of the chamber provides up to 40 percent more actual surface area (due to the circular tube crowns) — and therefore more heat transfer capability — and lower thermal strain (increased life) than smooth wall hot-side fabricated channel configurations. The tubular construction also provides improved pressure drop characteristics over rectangular channel designs.

A P&W-developed braze process joins the tubes to each other and to the coolant manifold rings. The manifolds are closed out prior to brazing to minimize risk of braze distress resulting from the weld process and to enable stress relief of the welds at temperatures higher than that planned for the braze process. After the braze, a fine grained electroform copper closeout of the tube crowns is applied followed by an electroform nickel plating for structural support. The assembled tube bundle of the AEC prior to braze is shown below in Figure 5.

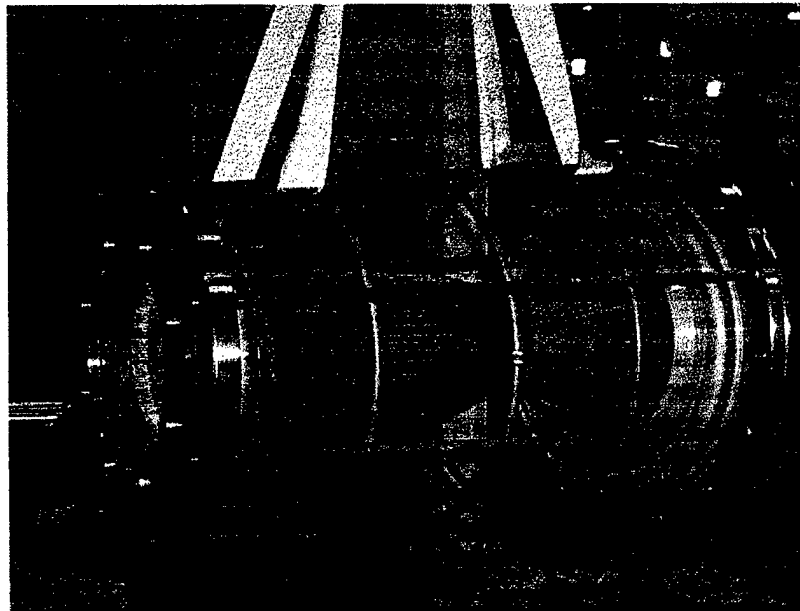


Figure 5 – Assembled Copper Tube bundle Prior to Braze

The three primary requirements for a successful braze process are braze temperature control, proper joint fit, and proper braze alloy placement. A low temperature gold germanium braze alloy was chosen for joining PWA 1177 because it has good braze coverage and sealing characteristics, good thermal conductivity, and a low diffusion interaction with the tubes. In addition, this braze material provides hydrogen compatibility so it will not react with hydrogen during brazing or operation.

Structural Jacket Design

The AEC structural jacket design is to provide thermal compatibility with the chamber liner, accommodation of hoop and axial loads, and a low risk manufacturing approach for demonstrating the copper tubular technology. The structural jacket is applied using an electroform plating process. Instead of bonding tube-bundle assemblies with braze alloy in a furnace braze

operation, the tubes are bonded with an electroformed deposit of copper and nickel done at essentially room temperature. Dimensional tolerances are significantly relaxed since precise fit controls are not necessary with electroform bonding. This approach is a proven viable method for producing thrust chambers. For the AEC, closeout of the PW1177 copper tubes is accomplished using a fine grained copper electroform plating process applied to a thickness of .040" above the tube crowns. This closeout is followed by an electroform nickel structural jacket approximately .250" thick

P&W has designed and fabricated an advanced injector compatible with the AEC, which may be used during testing of the AEC. This injector was designed for high combustion efficiency with minimal circumferential wall heat flux and mixture ratio variations. Tangential swirl elements were selected to provide a high degree of gaseous fuel and liquid oxidizer atomization, vaporization, and mixing. A torch ignitor design was selected for high performance and simplicity.

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of Fuel Inlet

Injector Design

AEC E8 Test Facility

A schematic of the E8 test facility is shown below as Figure 6.

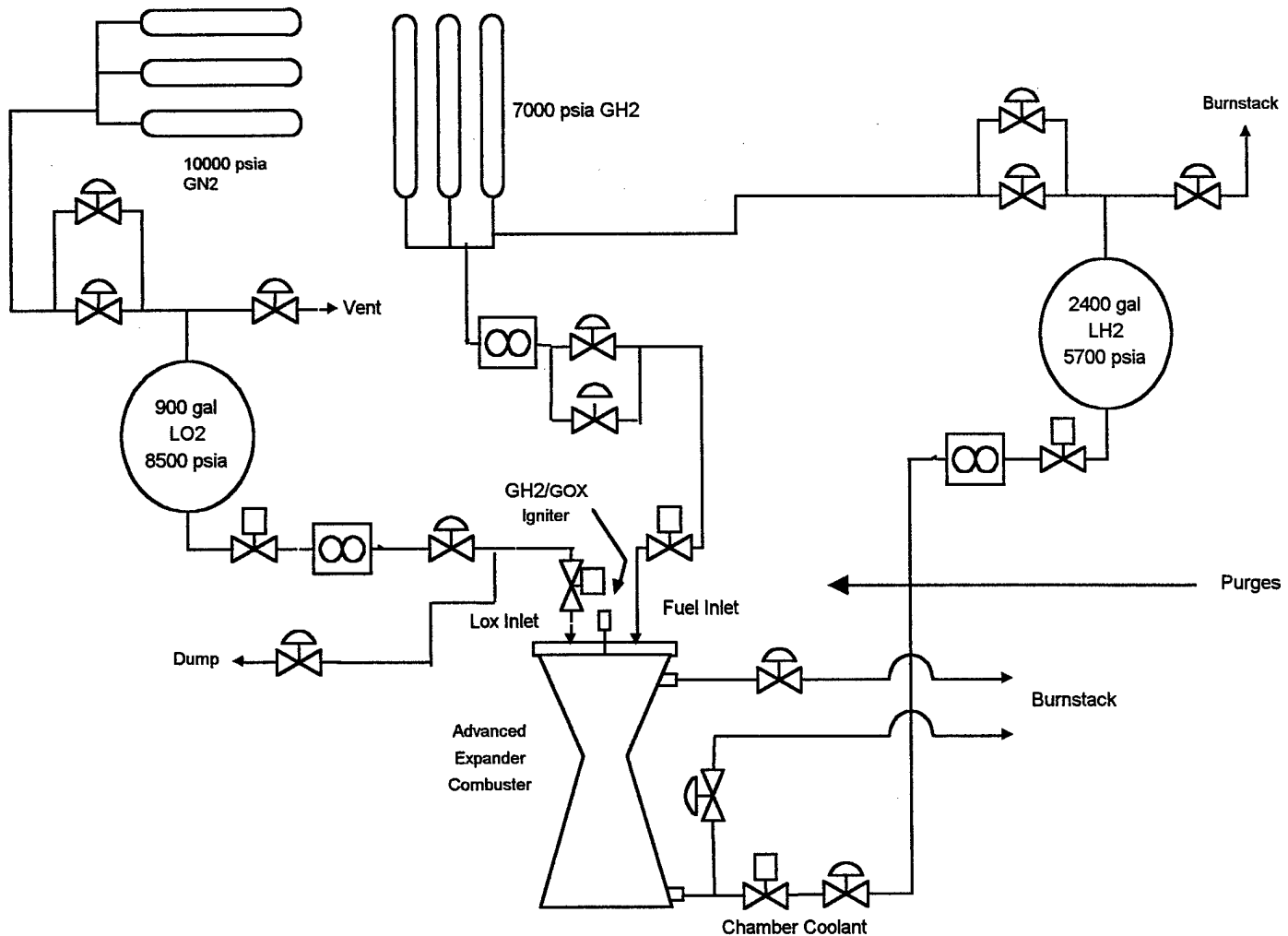


Figure 6 – AEC E8 Test Facility

In general, the facility is made up of three distinct sections. The high pressure liquid oxygen leg provides oxidizer to the test rig from a 900 gallon tank. GN_2 flow into the tank is controlled to maintain the tank pressure at 2100 psia. Two control valves are used for open loop scheduling of LOX to the test article. The high pressure GH_2 leg provides fuel to the test article from six GH_2 high pressure (7000 psia) storage vessels. Two control valves are used for open loop scheduling of GH_2 to the test article. The AEC coolant leg provides liquid hydrogen to the test article from a 2400-gallon tank. GH_2 flow into the tank is controlled to maintain the tank at 5700 psia. Two control valves are used for open loop scheduling of coolant flow to the test article.

AEC and Facility Model Overview

A transient math model for the AEC and test facility has been created with the P&W/NASA MSFC ROCKET Engine Transient Simulation (ROCETS) system. ROCETS consists of a library of module building codes, a processor to configure the modules into a user-defined system simulation and a processor to execute the simulation as defined by the user. The math model represents the AEC and facility through high fidelity physics and thermodynamics. Combustion properties are obtained from the NASA ODE database and real fluid properties from the NIST database.

The model incorporates:

- volume dynamics,
- facility plumbing line losses,
- multi-node AEC heat transfer characteristics,
- injector areas verified by water flow testing,
- valve characteristics and actuator dynamics,
- controller characteristics,
- active injector purges, and
- injector routine which accommodates both single phase and two-phase operation.

The model will be used to establish start, power level ramps, shutdown and steady-state sequencing procedures; support test planning; provide pre-run predictions; support plumbing design; define valve requirements; set purge flow requirements and define closed loop control methodology if needed. Preliminary valve and plumbing requirements are being defined with the transient model at this time. The hardware characteristics in the model will be

adjusted, if necessary, following cold flow testing of the valves and a phenolic checkout chamber.

CLOSE UP

Following this testing, the final requirements for testing of the AEC will be defined.

AEC Heat Transfer Model

The AEC heat transfer model simulates 6 thermal nodes along the axial flow path of the AEC. The model accounts for heat pickup from chamber combustion as well as ambient residual energy from the structural jacket and copper tubing. Figure 7 shows a cross sectional schematic of the heat transfer model. The particular heat flux components and directions, represented by the model, are shown in the schematic. Also shown is a table which describes the symbols used in the schematic.

AEC Validation Testing

Initial combustion system verification testing will be conducted on a phenolic chamber provided by the Air Force Research Laboratory. These tests include:

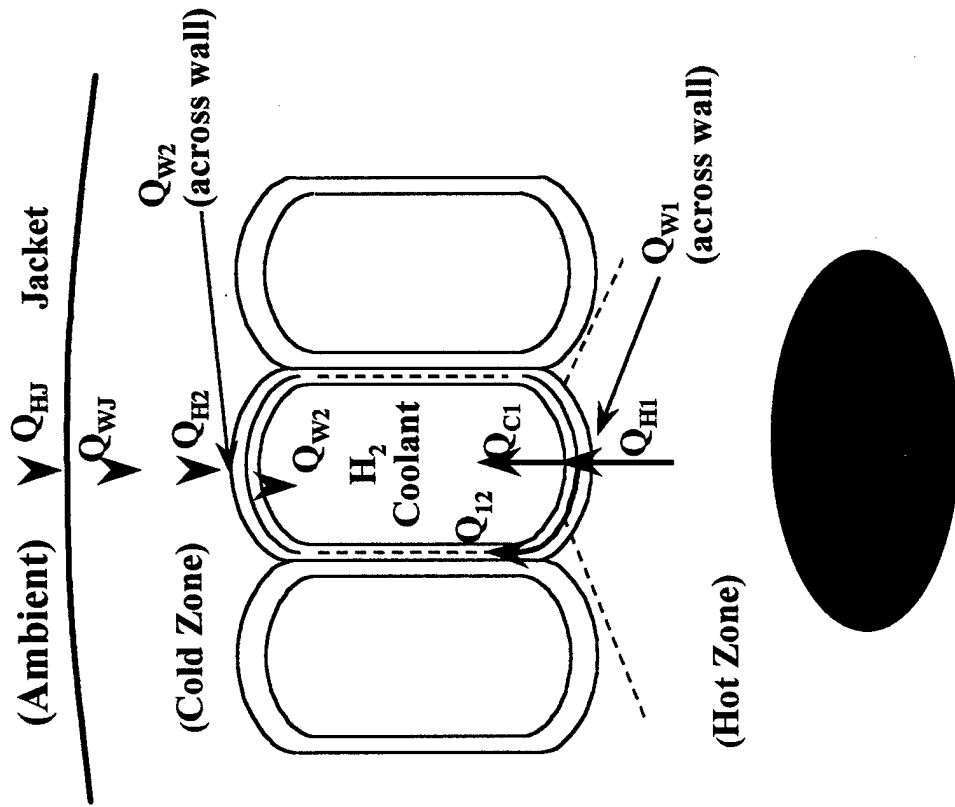
- facility flow characteristics,
- injector priming characteristics,
- ignition characteristics, and
- steady state and transient injector performance.

The phenolic chamber is being used to reduce the risk associated with the new injector design and facility uncertainties prior to mounting and testing the AEC.

Testing of the AEC will consist of hot firings to validate the combustion efficiency and stability as well as the AEC regenerative heat load. In addition, thermocouples attached to the backside of the copper tubes will be used to map the AEC heat flux profiles.

Information gathered through these tests will be used to update models for future design considerations of the Upper Stage Development (USD) engine system.

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Symbol	Heat Transfer Description
Q_{H1}	Hot Zone: Chamber to Comb. AEC Metal
Q_{W1}	Hot Zone: Comb. AEC Metal to Coolant Metal
Q_{C1}	Hot Zone: Coolant Metal to Coolant Flow
Q_{12}	Hot Zone: 2-d Conduction Hot Zone to Cold Zone
Q_{HJ}	Cold Zone: Amb. to Jacket Amb. Metal
Q_{WJ}	Cold Zone: Jacket Amb. Metal to Jacket Tube Metal
Q_{H2}	Cold Zone: Jacket Tube Metal to Coolant Tube Metal
Q_{W2}	Cold Zone: Coolant Tube Metal to Coolant Metal
Q_{C2}	Cold Zone: Coolant Metal to Coolant Flow

Figure 7.-AEC Heat Transfer Model

SUMMARY AND CONCLUSION

The AEC is expected to test at Pratt & Whitney's Florida test facilities in late-year 1999. The design has been completed and the hardware fabrication is nearing completion. The AEC test requirements are being integrated with the Air Force Research Laboratory in parallel with fabrication to ensure the facility is ready to support testing of the AEC on schedule.

Pratt & Whitney's Advanced Expander Combustor integrates state-of-the-art material, a high performance thrust chamber geometric configuration, and advanced fabrication approaches into a thrust chamber unit that supports the IHPRPT Phase I goals.

WHY ARE THERE
NO REFERENCES?